# Advanced Deep Space Systems Development Program Workshop on Advanced Spacecraft Technologies June 2-4.1997. Pasadena, CA Solar Power Portion of Proceedings - Part 1 of 6

## WORKSHOP BACKGROUND AND OBJECTIVES

*On* June 2-4, 1997, a workshop on Integrated Space Microsystems and Power was held at the Doubletree Hotel, Pasadena, CA. 'The workshop was co-sponsored by NASA/JPL and the Department of Energy (DoE). The technical committee consisted of Dr. Leon Alkalai, JPL (Chair); Dr. C. Perry Bankston, JPL; Dr. Joel Sercel, JPL; and Beverly Cook, DoE. The program chairs were Dr. Charles Elachi, JPL; and Dr. Carl Kukkonen, JPL. The honorary chairs were Daniel Goldin, NASA HQ; and Dr. Edward Stone, JPL.

## A. Background

NASA is currently considering a major initiative in the area of Advanced integrated Microsystems and Power Systems, for the massive exploration of space using micro-robotic systems such as micro-rovers, penetrators, planetary probes, micro-spacecraft, and other highly miniaturized and autonomous systems. For example, one of the spacecraft designs (referred to as the Second Generation Microspacecraft) weighs only 5.5 kg. These systems will require breakthroughs in highly integrated, low power, 3D packaging technologies, which are synergistic with ongoing trends in the commercial microelectronics applications, such as mobile computing and communication, nomadic systems, wireless communication, and portable computing.

To facilitate this development, JPL has started a complementary Advanced Deep Space System Development (ADSSD) Program. Its Seal is to facilitate technology validation in microelectronics and advanced power sources for future missions. Both solar and radioisotope power sources are targeted for development. The Department of Energy (DOE) issued a Program Research and Development Announcement (PRDA) later in FY 97, on the development of advanced radioisotope power sources for future deep space missions.

## B. ADSSD Program Objectives

- Develop, integrate and test *breakthrough* technologies
- Focus on the needs of challenging, exciting robotic science missions
- Develop broad long-range benefits to satellite, computer, and electronics industries

ADSSD will pull together activities from three diverse sources in order to make a unified program. The elements of the program include:

- Center for Integrated Space Microsystems (CISM)
- Advanced Power System Development (APSD)
- Advanced Experimental Spacecraft Testbed

ADSSD will pull together advanced technologies, integrate them within the Spacecraft Testbed and validate their performance and evolution to:

- assess their value and feasibility
- develop protoflight systems
- forecast flight readiness

## C. CISM Program Objectives

The objective of CISM is to develop fundamental technologies to build a "Spacecraft on a Chip". This unified approach will eliminate the barriers between subsystems. High level designs of power, avionics, and telecommunication "macro-cells" will be combined to form the right functions. Such macro cell designs will cut the design time dramatically. Specifically, CISM will:

- Develop subsystems enabling evolvable, reconfigurable spacecraft.
- Develop microelectronics technologies leading to "subsystems on a chip".
- Deliver subsystem components for flight validation.

Further information on CISM is available at their Website, http://cism.jpl.nasa.gov

## D. Advanced Power System Development (APSD) Program Objectives

The objective of APSD is to define, characterize and develop new high efficiency, low mass and low cost solar and radioisotope power sources for future deep space missions. Multifunctional systems, both solar and radioisotope, are essential because many, if not most, power system components are approaching, their maximum individual efficiencies. Breakthrough, innovative concepts for power conversion and heat sources are also keenly sought. Specifically, APSD will:

- Define requirements for innovative spacecraft power systems ranging from milliwatts up to several kilowatts (the latter primarily for solar electric propulsion).
- Develop innovative multifunctional power systems such as a radioisotope heater and power source, integrated apertures, the Power Antenna, and in situ propellant production ([ S1'1').

• Resolve key thermal control issues in advanced space power systems.

Further information on the New Millennium Program, which includes a number of key APSD applications, is available at the Website: http://nmp.jpl.nasa.gov

An APSD Website for JPL Radioisotope Power is under construction.

## E. Workshop Objectives

The overall objective of this workshop was to bring together leading experts in the field from industry, academia, and government laboratories to evaluate the current state of the art, and to contribute to future planning of strategically vital technologies,

### 1. For CISM:

- Develop concise plans leading to spacecraft subsystems on a chip implementation
- Ascertain the validity and applicability of integrated photonics/electronics, quantum and biological computing, and evolvable hardware.

### 2. For APSD - JPL OBJECTIVES

- Define and characterize advanced radioisotope power source (RPS) and advanced solar power source technology for the milliwatt to 100 watt class size range. Outputs are to include:
  - Technology readiness levels for these technologies
  - Applications of particular power source technologies
  - Anticipated technology development times
  - Figures of merit
  - Advantages relative to current state of the art
  - Present and proposed funding levels for technology development
  - Present and prospective advocates (Individuals and Organizations)

### 3. For APSD - DoE OBJECTIVES:

- Define and characterize Advanced RPS technology for future space missions. Specifically:
  - Define RPS design requirements and operational requirements
  - Determine what requirements drive RPS technology
  - Provide top level descriptions of potential future deep space scientific missions that may require RPSs
  - "Technology readiness levels for these technologies
  - Applications of particular power source technologies

- Anticipated technology development times
- Advantages relative to current state of the art
- Present and proposed funding levels for technology development
- Present and prospective advocates (Individuals and Organizations)

# Advanced Deep Space Systems Development Program Workshop

# on Advanced Spacecraft Technologies

# June 2-4,1997, Pasadena. CA

# Solar Power Portion of Proceedings-Part 2 of 6

## Workshop Agenda
## Day One: June 2, 1997
## CISM / Solar Power/ RPS Power

The viewgraphs from many of these talks arc available (just follow the links in Part 3)

| Topic | Speaker |
|---|---|
| Introduction | Leon Alkalai, JPL |
| WelcomingSpeech | Charles Elachi, JPL |
| Solar System Exploration Strategy | Doug Stetson, JPL |
| New Millennium Program Vision for 21st Century | Bob Metzger, JPL |
| Advanced Deep Space System Development Overview | Tony Spear, JPL |
| Advanced Technology Development Overview | Carl Kukkonen, J]'], |
| Phillips Laboratory Spacecraft Technology Developments | Christine Anderson, AFPL |
| Center for Integrated Space Microsystems Overview | Leon Alkalai, JPL |
| Power Systems Overview | C. Perry Bankston, JPL |

## Day Two: June 3, 1997
## CISM / Solar Power/ RPS Power
## Plenary and Overview Presentations

The viewgraphs from many of these talks are available (just follow the links in Part 3)

| Topic | Speaker |
|---|---|
| Ice and Fire Project | Rob Staehle, JPL |
| Mars Exploration Program | Sylvia Miller, JPL |
| Champollion/DS4 | Brian Muirhead, JPL |
| Advanced Deep Space Systems Development Program First Delivery | Dave Woerner, JPL |
| Advanced Deep Space Systems Development Program Future Delivery | Ross Jones, JPL |
| Integrated Space Microsystems Center of Excellence | Leon Alkalai, JPL |
| Interferometry Center of Excellence | Mike Shao, JPL |
| in Situ Center of Excellence | Carl Buck, JPL |
| Cassini/Galileo Power Source Review (presented to RPS Power attendees) | Beverly Cook. DoE |
| Advanced RPS Requirements (presented to RPS Power attendees) | Jack Mondt, JPL |

**Day Two: June 3, 1997**
**and Day Three: June 4, 1997**
**Power Breakout Sessions**

**(For the CISM parallel session, please see the CISM web site, http: //cism.jpl.nasa. gov)**

| Solar APSD | Radioisotope APSD |
|---|---|
| Breakout Sessions:<br>. Multifunctional Systems<br>. Integrated Apertures, Power Antenna, Flywheel Systems, ISPP<br><br>. Advanced Concepts<br>• Advanced Arrays, Advanced Batteries, Solar Electric Propulsion (SEP)<br><br>. Planetary in-Situ Power Systems<br><br>Applicable to Each Session:<br>. Thermal Control/Thermal Management<br>. Radiation Environment<br>• Temperature Effects<br>• AU Range | Breakout Sessions:<br>. Multifunctional Systems<br>• RHU/RPS<br><br>. Advanced Conversion<br>. Milliwatt Converter<br>• 10-20 watt Converter<br>• 50-100 watt Converter<br><br>. Advanced Heat Source Concepts<br>. Design<br>. Materials<br><br>Applicable to Each Session:<br>• Thermal Control/Thermal Management<br>. Radiation Environment<br>• Temperature Effects<br>• Impact Issues - g Forces (Penetrators/Landers)<br>. AU Range |

# Advanced Deep Space Systems Development Program Workshop

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# Solar Power Portion of Proceedings - Part 3 of 6

## Links to Plenary Talks (also available in the Agenda section)

### Day 1

Doug Stetson, JPL
http://cism.jpl. nasa.gov/randp/docs/stetson.pdf
Bob Metzger, JPL
http://cism.jpl. nasa.gov/randp/docs/metzger.pdf
Tony Spear, JP1.
http://cism.jpl. nasa.gov/randp/docs/spcarl .pdf
Carl Kukkonen, JP1,
http: //cism.jpl.nasa. gov/randp/docs/csn~t.pdf
I,eon Alkalai, JPL
http: //cism,jpl.nasa, gov/randp/docs/cism .presentation.02 .27.97.pdf

### Day 2

Rob Staehle, JPL
http: //cism.jpl.nasa. gov/randp/docs/staehlc. pdf
Sylvia Miller, JPL
http: //cism.jpl.nasa. gov/randp/docs/miller. pdf
and
http://cism.jpl.nasa.gov/randp/docs/miller2.pdf
Brian Muirhead, JPL
http://cism.jpl.nasa.gov/randp/docs/muirhead.pdf
Dave Woerner, JPL
http: //cisnl,jpl.nasa, gov/randp/docs/woerner. pdf
Ross Jones, JPL
http: //cism.jpl.nasa. gov/randp/docs/jones, pdf
I,eon Alkalai, JPL
http://cism.jpl.nasa.gov/randp/docs/cism.presentation.02.27.97.pdf

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# on Advanced Spacecraft Technologies
# June 2-4.1997, Pasadena. CA
# Solar Power Portion of Proceedings-Part 4 of 6

## NEW MILLENNIUM (SOLAR) SPLINTER GROUP OVERVIEWS

Three New Millennium splinter groups were implemented during the Workshop:

- Multifunctional Systems (e.g. integrated Apertures, Power Antenna, Flywheel Systems, In-Situ Propellant Production)
- Advanced Concepts (e.g. Advanced Arrays, Advanced Batteries, Solar Electric Propulsion)
- Planetary In-Situ Power Systems

Each session was requested to consider several common technological factors:

- Thermal Control/Thermal Management
- Radiation Environment
- Temperature Effects
- AU Range

The technical outputs for Multifunctional Systems and Advanced Concepts are summarized here and presented in detail in part 5 of these Proceedings. Planetary In-Situ Power Systems was absorbed by the other RPS and New Millennium splinter groups during the workshop.

## 1. SOLAR. ADVANCED CONCEPTS SPLINTER GROUP

### A. General Comments

There were 14 contributors with a wide variety of backgrounds.

(1) There were no flywheel advocates available in this group. We asked how low in power flywheel systems can be scaled.

(2) Thermal considerations as the spacecraft gets smaller need to be addressed earlier in the design than has customarily been done.

(3) 3'ethnology/systen~ options sheets on about a dozen technologies were generated.

## B. Mission Parameter Assumptions

(1) Mercury/Solar Polar

- Maximum Array Temperature 300°C
- Mission Duration 1 Year, 100 Orbits (Mercury)

(2) Mars In-Situ Propellant Production (ISPP)

- 2 kw/1kg $0_2$
- 120 kg Mass Limit

(3) Europa

- Duration 60 Days to 5 Years
- High Radiation
- SEP 2 kw at Europa

(4) Deep Space up to 40 AU

(5) Nominal Power 100 to 300 Watts

## C. Brief Descriptions Of Proposed New Technologies Or New System Concept.

(1) Inflatable - Rigidizable Structure

Supporting a copper iridium diselenide (CIS) solar array for multi-kilowatt solar electric propulsion (SEP). Estimated specific power 100-200 w/kg @1 AU.
Examples of applications include DS4/Champollion ( 12kw @1 AU, with aluminum laminate structure), and Europa Orbiter ( 12kw @1 AU, with gel-carbon structure)

(2) Large Inflatable Solar Concentrator

Specifically advantageous for outer planetary missions, combining a large, high quality solar concentrator that would focus light into a fiber optic bundle. The light would then be distributed directly to the instrument/spacecraft area that needed it. The light could then either be converted to electrical or thermal energy as required.

(3) Trough Solar Concentrator

This trough - configuration concentrator uses thin-film reflectors, allowing, a higher concentration ratio (2.5: 1 ) than conventional troughs, and a weight savings.

(4) Radiation Hard Solar Cells for Jupiter (Europa) Environment

Anticipated minimum dose is about 5 x $10^{16}$ 1 MeV electrons for 30 days. Candidate cells include either heteroepitaxial InP/Si or thin film cells.

(5) Modular Solar Electric Propulsion Stage (MEPS)

With internal concentrator and antenna and thermal control (Boeing patent pending).

(6) Solar Dynamic Power

Uses Brayton (turbine) or Stirling heat engine to convert solar energy to electric power. Particularly interesting for near-sun applications.

(7) passive Thermal Control for Electronics

Two devices are proposed for further development: First, compliant thermal bonds for diamond substrates and heat sinks. A technology called fiber flocking allows diamond substrate to form effective thermal bonds with metals. Second, graphite fiber thermal straps - with diamond end fittings - very useful in small, dense electronics - replaces heat pipes.

(8) Advanced Capillary Pumped Loop (ACPL)

This is a thermal transport system with a revolutionary (10X) heat flow rate relative to ordinary heat pipes, using multiple evaporators. The ACPL overcomes the startup and vapor lock problems associated with CPL's. This system is ideal for dense electronics packaging because the reservoir is remote from evaporators, and a single loop to/from the radiator serves all the evaporators.

(9) Loop Heat Pipe (LHP)

A self starting, self regulating, self contained two phase heat transfer system.

(1 O) Primary Lithium Interhalogen Battery

$Li-BF_3 . ICl_3$

(11 ) Lithium - Ion Rechargeable Battery

$LiC_6$ - $LiCoO_2$
$LiC_6$ - $LiNiO_2$
$LiC_6$ - $LiMn_2O_4$
ormixed oxides

(12) Low Temperature RechargeableLi Battery

Li / $SO_2$-C
Li / $LiAlCl_4$-6$SO_2$ / $CuCl_2$

(13) Lithium-Polymer RechargeableBattery

Single-ion lithiumconductor.

## 2. SOLAR ENERGY MULTIFUNCTIONALSYSTEMS SPLINTER GROUP

## A. General Comments

There were 10 participants in the splinter group:

Dave Barnett, Chair, LMA
Kent Decker, TRW
Costa Cassapakis, L'Garde
Steve Bitterly, USFS
Jack G. Bitterly, USFS
Jeff Schreiber, LeRC
Martin Buehler, JPL
Hoppy Price, JPL
Carol Lewis, JPL
Tosh Fujita, JPL

## B. Brief Descriptions Of Proposed New Technologies Or New System Concepts

### (1) Flywheel Energy Storage And Attitude Control

Flywheel energy storage and attitude control system that leverages technology activities for terrestrial applications and offers major potential savings in spacecraft systems by simultaneously satisfying two key system requirements.

### (2) Power Antenna

- A lightweight, small stowed inflatable solar concentrator doubling up as a communications antenna capable of large data-transfer rates.
- A body mounted PV array or AMTEC converts the concentrated solar flux at the focal plane, while a grid mounted between the reflector and focal plane diverts the RFD energy onto a side-mounted feed (& vice-versa).
- Can be used en route to an exoplanetary rendezvous by using a solar flux attenuator when close to 1 AU.
- Non-nuclear with masses of the same order as RTGs.

### (3) Multifunctional Structures (MFS)

MFS integrates electronics with structures and thermal control and will enable cable free spacecraft in its ultimate embodiment. An experiment to validate key features is to be flown on DS-1 and this will provide the basis for validation of an MFS integrated into a spacecraft,

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# on Advanced Spacecraft Technologies

# June 2 - 4, 1997, Pasadena, CA

# Solar Power Portion of Proceedings-Part 5 of 6

## DETAILS OF NEW TECHNOLOGIES OR NEW SYSTEM CONCEPTS

## A. ADVANCED CONCEPTS SPLINTER GROUP

### (1) INFLATABLE- RIGIDIZABLE STRUCTURE

**Description: (Brief description of the new technology or new system concept.)**

Technology - Inflatable - Rigidizable Structure supporting a copper indiurn diselenide (CIS) solar array for multi-kilowatt solar electric propulsion (SEP). 100-200 w/kg @1 AU.

examples: DS4/Champollion
12kw @1 AU (aluminum laminate structure)
Mission: SEP to comet

Europa Orbiter
Mission: SEP
12kw @ 1 AU (gel-carbon structure)

Packaging: Compact and conformal.
Pointing: 2-axis, “slow”

Mission Type - Requirements Range: (SEP)

| | Champollion | Europa |
|---|---|---|
| Maximum Acceleration | 0.01 g | 0.1 g+-+ |
| Natural Frequency: | 0.03 Hz | -0.1 Hz |
| Radiation: | No coverglass | 2-20 mil thick coverglass |

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

Enabling for mass constrained and launch volume constrained missions, such as SEP

**Technical Maturity: (When could this technology be flight ready if funded?)**

Previous Programs:

ITSAT - ground qualification of aluminum laminate inflatable-rigidizable frame solar array.

IRD - gel-carbon rigidization development

Could be ready to fly well before year 2000

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

1) Positively controlled deployment
2) Final shape and structural capability
3) Environmental response of structure and its materials

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

Planning underway to address issues in JPL and GSFC technology development programs (near-term)

**Resources: (Describe funding, who is doing the work and where it is being done)**

**Advocates: (Individuals and Organizations)**

Inflatable - Rigidizable Structures - I.'Garde, Inc.
Sponsored by: JPL, GSFC

## (2) **LARGE INFLATABLESOLAR CONCENTRATOR**

**Description: (Brief description of the new technology or new system concept.)**

Large Inflatable Solar Concentrator.

Specifically advantageous for outer planetary missions, combining a large, high quality solar concentrator that would focus light into a fiber optic bundle. The light would then be distributed directly to the instrument/spacecraft area that needed it. The light could then either be converted to electrical or thermal energy as required.

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

Attempts to perform outer planetary missions using solar suffer not only from power constraints from the diminished solar flux, but also thermal problems (many instruments must be kept warm in order to work) This concept tries to maximize the solar power available for both power and heat, and allows easy switching between the two. Could also minimize/eliminate PMAD losses and equipment. Could be extremely radiation hard solar option for Jupiter mission. Could also build in redundancy through optical switching demonstration.

**Technical Maturity: (When could this technology be flight ready if funded?)**

Many of the components necessary are being worked on individually. No system integration of the necessary components has been demonstrated or planned. An integrated program would need to be put together. Prototype system could probably be demonstrated by 2002/2003 time frame.

**Technical issues/Risk: (Describe the technical issues and the probability/time for resolution)**

Largest technical risk in

- Large inflatable concentrator
- Fiber optic cable; secondary/fiber optic interface
- Cell development at light-to-electrical interface

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

- Demonstrate large inflatable concentrator

- Integrate concentrator with fiber optic cable
- Demonstrate fiber optic- to-receiver element (light to electrical/thermal energy)
- Demonstrate working end-to-end system

**Resources: (Describe funding, who is doing the work and where it is being done)**

- NASA Lewis/Entech Inc. is working on large inflatable and refracting secondary concentrators.
- Physical Sciences/NASA JSC is developing fiber optic transport of light for material processing application.
- Kopin Corporation demonstrated, many years ago, the type of PV cell technology necessary.

**Advocates: (Individuals and Organizations)**

Michael Piszczor/NASA Lewis
Mark O'Neill/Entech, Inc.
Takashi Nakamura/Physical Sciences

## (3) TROUGH SOLAR CONCENTRATOR

**Description: (Brief description of the new technology or new system concept,)**

Solar Concentrator. This trough - configuration concentrator uses thin-film reflectors, allowing, a higher concentration ratio (2.5: 1) than conventional troughs, and a weight savings.

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

**- 55%** reduction in cell requirements; specific power over 100 w/kg; packing of about 600w/ft$^3$. This translates into weight savings and/or power increases.

**Technical Maturity: (When could this technology be flight ready if funded?)**

**-18** Months

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

**1.** Large reflector fabrication and deployment (4 months)
2. Thermal vacuum solar simulator test (8 months)

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

**See** Above

**Resources: (Describe funding, who is doing the work and where it is being done)**

Present funding - $350K - wc need a demo flight, sponsor for flight integration costs.

**Advocates: (Individuals and Organizations)**

NRL - Mike Brown (202) **767-2851**
SRS (Huntsville, AL)

## (4) RADIATION HARD SOLAR CELLS

**Description: (Brief description of the new technology or new system concept.)**

Use of radiation hard solar cells for Jupiter (Europa) environment

$5 \times 10^{16}$ 1 MeV electrons for 30 days

Either heteroepitaxial InP/Si or thin film cells.

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

In either planar or concentrator arrays, much less shielding required, hence lower mass arrays.

**Technical Maturity: (When could this technology be flight ready if funded?)**

2 to 3 years.

(1) Thin film cells need some more space-related attention; they are in production for terrestrial applications.

(2) Higher efficiency InP-based multifunction cells are in a manufacturing technology (MANTECH) program.

**(3)** The InP/Si cell, while having lower beginningof life (BOL) efficiency, should have about the same end of life (EOL) performance.

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

(1) Unknown Jupiter radiation environment

(2) Development and production of space qualified thin film cells: copper indium gallium diselenide (CIGS), amorphous Si

**(3)** Production of InP/Si cells

(4) Radiation damage coefficient measurements on production cells

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

(1) Better understanding of Jupiter (Europa) radiation environment

(2) Measurements at a variety of energies of radiation performance of cells.

**Resources: (Describe funding, who is doing the work and where it is being done)**
(1) Thin film cell development (CIGS, CdTe, amorphous Si) is heavily supported primarily for terrestrial PV; however, DARPA (CIGS) and TRW (amorphous Si) are active in space cell development,

**(2)** Essential Research (NASA funded) is developing InP/Si. NRL is quite active in multifunction InP cell development.

**Advocates: (Individuals and Organizations)**

InP - NRL, NASA, Essential Research

Thin film cells - terrestrial PV community, TRW, DARPA; perhaps interest from LEO satellite constellation manufacturers

## (5) MODULAR SOLAR ELECTRIC PROPULSION STAGE

**Description: (Brief description of the new technology or new system concept.)**

Modular Solar Electric Propulsion Stage (MEPS) with internal concentrator and antenna and thermal control (Boeing patent pending)

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

- MSEPS:
  - . Combining power source, attitude control, and propulsion for orbit raising
    - . Replaces reaction wheels, array deployers, orientation drives and power transfer mechanisms
  - . Direct drive microthrusters distributed on spherical array provide steering
  - High voltage solar array (probably thin film cells) provides direct drive to Hall thrusters over most sun angles

Add solar concentrator, antenna, and thermal control:

- . Concentrator collects solar energy for electrical and thermal in LILT conditions beyond 2 AU
- . Pointing antenna adequate for solar concentrator

**Technical Maturity: (When could this technology be flight ready if funded?)**

3 to 5 years. 1 year demonstration (small scale about 3 m diameter)

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

. Direct drive microthrusters - dedicated array segments -100 V (0.5 to 3 watts) - pulse control method - concept proof of principle, 1 year

- Folding internal antenna and feed - packaging for storage/deployment. Geometry demo 1 year
- Local structural "load" and stiffness relationship to attitude control from microthruster pulses - control law analysis -9 months
- Microarray (Boeing patent pending) concentrating array at "soft focus" of concentrator - demo 1.5 yr.

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

- Spherical array with concentrating lens
  - Thin film array/electrical circuit design
  - Concept demo -1 year
- Scale up and packaging demo -2 years
- Functional prototype 3-5 years

**Resources: (Describe funding, who is doing the work and where it is being done)**

Boeing has funded microarray development

**Advocates: (Individuals and Organizations)**

Paul Dillard, Boeing Defense and Space Co.
Research and Technology
Space Power Technology

## (6) SOLAR DYNAMIC POWER

**Description: (Brief description of the new technology or new system concept.)**

Solar Dynamic Power

Uses Brayton (turbine) or Stirling heat engine to convert solar energy to electric power.

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

1. Allows efficient power generation for near-sun operations. In this case SD can be operated without a concentrator - working with heat coming through the heat shield.

2. SD is radiation tolerant, without degradation.

**Technical Maturity: (When could this technology be flight ready if funded?)**

1. Brayton technology is fully mature - estimated 18 months to deliver flight article.

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

1. Advanced, lightweight receiver needs to be demonstrated (but note that near-sun application uses a simple flat plate receiver, and no concentrator!)

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

Design and analysis for near-sun flight demo (even if done near earth) needs to be done. Ground demo can probably suffice - use solar concentrators @ Sandia Labs.

**Resources: (Describe funding, who is doing the work and where it is being done)**

1. Design and costing of ground demo: 9 months, $700K.
2. Ground Demo: Rough estimate $4M.
3. Work is being done @ NASA/Lewis, with support from NRL (Spacecraft Design interface) and Allied Signal (Bray ton Engine).

**Advocates: (Individuals and Organizations)**

**NASA Lewis, NRL,** Allied Signal

## (7) PASSIVE THERMAL CONTROL FOR ELECTRONICS

**Description: (Brief description of the new technology or new system concept.)**

Passive Thermal Control for Electronics

Two devices are proposed for further development:

1. Compliant thermal bonds for diamond substrates and heat sinks. A technology called fiber flocking allows diamond substrate to form effective thermal bonds with metals.

2. Graphite fiber thermal straps - with diamond end fittings - very useful in small, dense electronics - replaces heat pipes.

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

These devices will reduce the mass of thermal control systems in electronics packaging by replacing metal conductors and heat pipes. They offer at least a revolutionary (10X) increase in specific thermal conductivity,

**Technical Maturity: (When could this technology be flight ready if funded?)**

*12* Months

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

The only technical issue is finding the correct way to braze the graphite fibers and diamond fittings together. Solution expected in 6 months.

The only real problem is in forming a working relation with electronics designers.

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

Complete demonstrations using thermally stressed components in working electronics boxes.

**Resources: (Describe funding, who is doing the work and where it is being done)**

- $350K/year in FY'97 for work done @ NRL and contractor ESLI. Sponsor is being "rescoped", funding will probably not continue into 1998.

**Advocates: (Individuals and Organizations)**

NRL - Mike Brown - #(202) 767-2851
ESLI

(8) **ADVANCEI) CAPILLARYPUMPED LOOP (ACPL)**

**Description: (Brief description of the new technology or new system concept.)**

Advanced Capillary Pumped Loop (ACPL)

This is a thermal transport system with a revolutionary (10X) heat flow rate relative to ordinary heat pipes, using multiple evaporators. The ACPL overcomes the startup and vapor lock problems associated with CPL's. This system isideal for dense electronics packaging because thereservoir is remote from evaporators, and a single loop to/from the radiator serves all the evaporators,

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

1. Greatly reduces mass of thermal control system.
2. 10X greater heat transport - lower operating temp. for electronics.
3. High pumping head in fluid loop allows 3-D routing of heat flow, single test of system.
4. Allows very dense packing of electronics - put any size evaporators wherever they are needed.
5. Flexible lines allow use in deployable radiators.

**Technical Maturity: (When could this technology be flight ready if funded?)**

12 to 18 months.

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

TBD

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

Complete ground experiment must be built and tested.

**Resources: (Describe funding, who is doing the work and where it is being done)**

Work is being done@ NRL.

**Advocates: (Individuals and Organizations)**

**NRL -** Mike Brown (202) 767-2851; NRO

## (9) LOOP HEAT PIPE

**Description: (Brief description of the new technology or new system concept.)**

Loop Heat Pipe (LHP) is a self starting, self regulating, self contained two phase heat transfer system. See sketch for additional information.

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

High heat transport
Low AT (low thermal resistance)
Passive or controllable operation
Lightweight
Flexible (deployable) transport lines

**Technical Maturity: (When could this technology be flight ready if funded?)**

Flight test - November 1997
Commercial satellite launch -1998

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

Design and operation below 10OW needs to be demonstrated. With funding, can be flight qualified within a year.

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

Demonstration of scaled down design

**Resources: (Describe funding, who is doing the work and where it is being done)**

High heat flux LHP - Funded by NASA-Goddard. Work by Thermacore
Multichip Module - NASA Lewis / Center for Space Power, Texas A&M / Thermacore
Advanced Commercial - Hughes / Dynatherm

**Advocates: (Individuals and Organizations)**

Hughes Space & Communications
NASA
NRL
BMDO/DoD/WPL/PL
Center for Space Power - Texas A&M
Thermacore
Dynatherm
Lockheed Martin
Loral Space

## (10) PRIMARY LITHIUM INTERHALOGEN BATTERY

**Description: (Brief description of the new technology or new system concept.)**

Primary Lithium Interhalogen Battery
$Li\text{-}BF_3, ICl_3$

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

. Significant reduction in primary battery weight and volume; > 60() Whr/kg
> 500 Whr/l

. Bipolar configuration gives Hi-G capability.

**Technical Maturity:** (When **could this technology be flight ready if funded?)**

At basic research stage.
. This technology, in reserve configuration, could be ready in 2003 time frame.

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

*2000* Chemical compatibility with oxyhalide electrolyte blend and for long term storage.
2001 Low temperature kinetics
2001 Materials stability (chemical/physical) for novel reserve concepts for radiation, landing, etc.
2003 Battery integration issues resolved.

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

- Establish chemistry along with component stability
. Develop mechanical aspects of reserve battery
. Develop manufacturing/quality control processes/procedures
. Demonstrate prototype systems

**Resources: (Describe funding, who is doing the work and where it is being done)**

. No effort currently in progress as of 6/97

. Navy (China Lake) and AF (WL/POOB) had basic effort in past

**Advocates: (Individuals and Organizations)**

Air Force WL/POOB - Mr. Marsh
Navy (China Lake) - Dr. Miles

## (11) LITHIUM- ION RECHARGEABLE BATTERY

**Description: (Brief description of the new technology or new system concept.)**

Lithium - ion Rechargeable Battery

$LiC_6$ - $LiCoO_2$

$LiC_6$ - $LiNiO_2$

$LiC_6$ - $LiMn_2O_4$

or mixed oxides

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

. Major reduction in power system mass and volume

- Cell level -150 Whr/kg and 300 Whr/l
- Battery level projection 100 Whr/kg
  200 Whr/l
  pulsed power -1 kw/kg

. Reduced power system and launch costs

. Coulombic efficiency- 100%

. Energy efficiency $\geq$ 90%

**Technical Maturity: (When could this technology be flight ready if funded?)**

. Flight batteries 2001 for limited cycle missions

. GEO batteries 2002 (>2000 cycles)

• LEO batteries 2003 (>30,000 cycles)

• Small cells (1.2 amp-hour) commercially available for consumer electronics

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

• Low temperature performance (2000)

. Long cycle life (i.e. LEO) and long term chemical stability need to be established (2003)

. Electro-thermal control system for battery needs to be developed (2001)

. Scale-up to large cells (1.2 Ahr $\rightarrow$ >20 Ahr) (2001)

. Manufacturing processes/quality control at cell level (2001 )

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

- Establish optimum chemical systems for aerospace applications
- Establish optimum anode structure/material
- Demonstrate cycle life - accelerated mode and chemical compatibility
- Develop smart battery system

**Resources: (Describe funding, who is doing the work and where it is being done)**

- Current effort at cell level=> DARPA, USABC, Air Force, JPL and Army ≥ $ 50M over past five years

DoD/NASA Li-ion battery development effort planned at> $ 25M over five years

**Advocates: (Individuals and Organizations)**

US Air Force, NASA/JPL - Space Applications

DOE/USABC - ElectricVehicles

Yardney Tech Products, Eagle-Picher, SAFT America

## (12) LOW TEMPERATURE RECHARGEABLE Li BATTERY

**Description: (Brief description of the new technology or new system concept.)**

Low Temperature Rechargeable Li-Battery

$Li / SO_2\text{-}C$

$Li / LiAlCl_4\text{-}6SO_2 / CuCl_2$

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

- Operates at $-80^0C$
- Room temperature energy >200 Whr/kg; 300 Whr/l at cell level
- Cycle life >800 cycles

**Technical Maturity: (When could this technology be flight ready if funded?)**

- Cell level technology- experimental level
- $Li\text{-}SO_2$ using new reaction site structure could provide significant improvements
- Currently being worked by USAF for low temperature, limited cycle aviation battery
- Could be flight ready for specific missions by 2001 for limited cycle low temp applications

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

- Scale up to large cells >10 Ahr (2000)
- Manufacturing and quality control procedures/processes (2000)
- Battery thermo-electrical control system, charger/controller (2001)

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

- Construct large cells (>10 Ahr)
- Develop materials for $SO_2$ reaction sites which have good mechanical/chemical stability
- Develop manufacturing processes, material controls and quality control limits

**Resources: (Describe funding, who is doing the work and where it is being done)**

- USAF/BMDO - managed by WL/POOB
- Preliminary work by Duracell and funded by DoE on Li-$S0_2$
- German government doing some development in Germany

**Advocates: (Individuals and Organizations)**

U.S. Air Force (WL)
BMDO
German Government/old GTE group

(13) **LITHIUM - POLYMER RECHARGEABLE BATTERY**

**Description: (Brief description of the new technology or new system concept.)**

Lithium-polymer rechargeable battery.

Sing! e-ion lithium conductor.

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

. Gravimetric/volumetric energy $\rightarrow \geq$ 300 Whr/kg
$\geq$ 500 Whr/l
. Electrolyte with conductivity $\geq$ 10-2 S/cm at room temperature (RT) with AH -0 across temperature spectrum
• Configurationally independent - battery could be part of spacecraft structure
. Multifunctional system with significant cost reductions in power system and launch

**Technical Maturity: (When could this technology be flight ready if funded?)**

. Theoretical concepts established
. Cell level technology and manufacturing processed developed by 2005 $\pm$ 3

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

2000 . Synthesis of single-ion lithium conductor with conductivity> 10-2 S/cm at RT, with small AH across temperature spectrum from -60°C to +80°C
2005 . Thin film manufacturing processes
2005 . Chemical stability of true polymer system
2008 . Demonstrate battery energy densities, power densities and cycle capability

**Kcy Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

1999 - Synthesis of single-ion (channel) lithium conductor@ 10-2 S/cm conductivity
2000 - Prototype battery - experimental units
2005 - Configurationally independent, high voltage battery system

**Resources: (Describe funding, who is doing the work and where it is being done)**

US Air Force - Wright Laboratory (AFWL)
- 600K/yr for basic research

DARPA/NASA, AFPL, Army, Navy:
Gel electrolyte polymer systems at -$ 1-2 M/yr over past 3 years

DoE/USABC
Electric Vehicle >$ 30M over past 5 years

**Advocates: (Individuals and Organizations)**

US Air Force
DoE/USABC/PNGV

## B. SOLAR ENERGY MULTIFUNCTIONALSYSTEMS SPLINTER GROUP

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**(1) FLYWHEEL ENERGY STORAGE ANI) ATTITUDE CONTROL**

**Description: (Brief description of the new technology or new system concept):**

Flywheel energy storage and attitude control system that leverages technology activities for terrestrial applications and offers major potential savings in spacecraft systems by simultaneously satisfying two key system requirements.

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

- Approximately 3X lighter than present battery technology ($Ni$-$H_2$), considering storage, attitude control and some electronics
- Long cycle life at 90% depth of discharge (DOD)
- Round trip energy efficiency > 85°/0
- Precise energy measurement with wheel speed
- Wider operational temperature range than batteries
- No taper charging required
- Extremely high power density (pulse mode)
- Built-in sensor capabilities
- High gain magnetometer
- Gravity detection via magnetic bearings
- Potential gyroscopic stability for rovers and planetary probes
- Provides rotational means for penetrator

**Technical Maturity: (When could this technology be flight ready if funded)**

- Terrestrial flywheels are currently exhibiting 20 w hr/lb
- Flight prototype flywheel programs initiated in FY 97
- Flywheel flight demo within 5 years

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

- Need to determine minimum feasible scaling boundary and configuration tradeoffs
- Need launch and landing impact vibration and shock analysis
- Need life cycle data under mission conditions
- Need analysis of spacecraft disturbances
- Need assurance of safety containment

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

- Test bed demonstrations of counter-rotating wheels
- Requirements analysis/preliminary design effort
- Prototype development/demonstration
- Life cycle verification of prototype
- Completion of containment safety study with verification

**Resources: (Describe funding, who is doing the work and where it is being done)**

- NASA LeRC: Task order contracts with TRW/USFS
- DARPA: Life cycle testing, containment testing
- Aberdeen Proving Ground: Shock and vibration
- Phillips Laboratory: IPACS study with Satcon
- Air Force: Test bed demo with Hughes/Satcon
- LeRC/JSC: ISSEC flight demo with Boeing
- Texas A & M: Control algorithms

**Advocates: (Individuals and Organizations)**

National Labs: Argonne, Lawrence Livermore, NREL, INEL, NASA LeRC, NASA JSC, NASA GSFC

Companies: TRW, Hughes, Boeing, US Flywheel Systems, Satcon, Teldix

(2) **POWER ANTENNA**

**Description: (Brief description of the new technology or new system concept):**

- A lightweight, small stowed inflatable solar concentrator doubling up as a communications antenna capable of large data-transfer rates.
- A body mounted PV array or AMTEC converts the concentrated solar flux at the focal plane, while a grid mounted between the reflector and focal plane diverts the RFD energy onto a side-mounted feed (& vice-versa).
- Can be used en route to an exoplanetary rendezvous by using a solar flux attenuator when close to 1 AU.
- Non-nuclear with masses of the same order as RTGs.

**Benefits/Figure of Merit: (How will this technology/system concept improve space missions)**

- Can potentially provide electric power for exoplanetary or deep space missions without the political complications of RTGs and at an order of magnitude lower cost.
- The same system will enable high date rate communications.

**Technical Maturity: (When could this technology be flight ready if funded)**

Circa 2001 (based on planned flight demo).

**Technical Issues/Risk: (Describe the technical issues and the probability/time for resolution)**

- Ample concentration ratios at small working pressures
- Controlled deployment
- Structure rigidization
- Pointing accuracy of concentrator system
- Effect on spacecraft attitude control (for very large antennas)

**Key Milestones: (Experiments/analyses required to resolve technical issues and reduce risk)**

- Demo large concentration ratios, low weights at small pressures--Sept 97
- Controlled deployment demo in early 1999
- Structure rigidization demo in early 1999
- Ground system test in early 2001; flight demo to follow

**Resources: (Describe funding, who is doing the work and where it is being done)**

. IR&D: I,'Garde, Inc.. Tustin, CA
• NASA Inflatables Program: JPL, I.' Garde, other industrial partners
. Large Inflatable Structures Program: Phillips Lab, L' Garde
. Power Antenna Phase II SBIR: L' Garde

**Advocates: (Individuals and Organizations)**

. Costa Cassapakis, Leo Lichooljieieski, L'Garde
. JPL Modular and Multifunctional Systems (MAMS) Integrated Product Development Team (IPDT) and Inflatable Programs
    . Joel Sercel, Art Chmielewski, Bob Freeland, Carol Lewis

### (3) MULTIFUNCTIONAL STRUCTURES (MFS)

This technology is being developed by the Air Force Phillips Lab and Lockheed Martin Astronautics, and is being pursued as a New Millennium IPDT technology.

MFS integrates electronics with structures and thermal control and will enable cable free spacecraft in its ultimate embodiment. An experiment to validate key features is to be flown on DS-1 and this will provide the basis for validation of an MFS integrated into a spacecraft.

This step will involve collaborative efforts among the MAMS, Microelectronics, and ISM IPDTs. This workshop provided an opportunity to kick off the collaborative work.

# Advanced Deep Space Systems Development Program Workshop

# on Advanced Spacecraft Technologies

# June 2-4.1997. Pasadena, CA

# Solar Power Portion of Proceedings- Part 6 of 6

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